Magnetic Domain Analysis of PM Generator yields OU Operation
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1. Introduction

I have known for some years that it is possible to load the spinning or orbital electrons responsible for permanent magnetism so that they deliver energy. This is easily demonstrated when considering the summated magnetic fields from a magnet and from a coil wound around the magnet. It can be shown that some of the magnetic field energy comes from the magnet and not from the coil, when the coil is adding energy the changing flux draws energy from the atomic spins within the magnet. Until now I have not found a method of using this loading effect to get power delivered to a load resistor, it has always appeared as field energy that gets clawed back on a later part of the cycle. However having recently been driven to analyse a PM generator in the magnetic domain, and not in the electric domain, the conditions for making the atomic spins supply power to a load have been revealed. This paper deals with that perspective and could open the door to overunity generators that extract some of their energy from the quantum domain that keeps the atomic spins going.

2. Magnetic Domain Analysis

Here we describe a method for the dynamic analysis of systems in the *magnetic* domain. In a manner it is the inside-out version of the electrical equivalent circuit. The magnetic "circuit" is modeled along well-known lines where magnetic flux is treated like current and magnetic reluctance like resistance. However it goes beyond the simple "magnetic Ohm's Law" by introducing other magnetically reactive components that represent the outside electrical world. This allows a time or frequency domain analysis to be carried out on the magnetic flux, from which the electrical characteristics automatically follow. Such a procedure gives a deeper insight into the magnetic behaviour, and enables more accurate modeling of unusual systems or those working outside their normal envelope.

"Magnetic Ohm's law" will be found in any good treatise on magnetism, and is repeated here for completeness and as a starting point. Magnetic reluctance R_M is treated like electrical resistance R, magnetic flux Φ like current I, and mmf U like voltage V. Hence the mmf drop across a length of core material of reluctance R_M is given by

$$U = \Phi R_M \tag{1}$$

which is the magnetic Ohm's Law equivalent of $V=IR$. And just as the resistance of a rod of resistive material is given by $R=l/\sigma A$ where l is the length, A the cross sectional area and σ the conductance, so the reluctance of a rod of ferromagnetic material is

$$R_M = \frac{l}{\mu A} \tag{2}$$

where μ is the absolute permeability. Treating sections of the magnetic circuit in this way enables the reluctance of a core made up of different cross sections to be determined. Also the distribution of flux among different branches of a complex core arrangement can be determined by solving as a network of reluctances. Air paths also have reluctance, and when these are confined to small gaps the formula $R_M = l/\mu_0 A$ can be used. However when flux spreads out within air it requires other methods such as those used for establishing capacitance between bodies. Generally the reluctances of air gaps and of permanent magnets are so high that, similar to electric circuits that have wires of high where their resistance is considered to be zero, magnetic circuits can have ferromagnetic core sections whose permeability is so high that their reluctance can also be taken to be zero.

For a coil the *magnetic* reluctance plays its part in the *electrical* inductance as

$$L = \frac{N^2}{R_M} \qquad (3)$$

where N is the number of turns and R_M is total reluctance of the closed air paths through and around the coil. When the coil carries a current I its mmf is $U=NI$ ampere turns, hence "magnetic Ohm's Law" gives the self-flux through the coil as $\Phi_{self}=NI/R_M$. Thus self-flux $\Phi_{self}=LI/N$ (not to be confused with flux *linkage* which is often loosely called flux and given as $\Phi_{self}=LI$). In a classic generator the self-flux from load current through the coil is known to distort the flux pattern through which the coil is moving, leading to armature reaction. This requires the brushes on the commutator to be moved to a new position aligned with the distorted flux in order to achieve maximum performance. This is generally a movement of a few degrees, anything greater is not normally considered as it is assumed to be deleterious to the generation process. This conception is shown to be wrong in the full analysis carried out later in this paper which shows that under certain conditions it shifts the phase of the load current from an armature position where the load current creates drag torque to one where it doesn't.

Permanent magnets can be modeled from their Amperian Surface Current equivalent which then appears as a mmf generator whose value is given by

$$U_M = \frac{B_{REM}\, l}{\mu_0} \qquad (4)$$

where B_{REM} is the remanence and l is the length of the magnet. This must be put in series with a reluctance R_{MAG} which is the reluctance of the *air space* occupied by the magnet. That air space represents the large inter-atomic space that separates the individual electron spins which supply the magnetism, and the justification for this model can be found in the well known method for determining the magnetic load line that involves the reluctance of that air space.

If we now turn to coils through which flux is changing, the output voltage is $N\mathrm{d}\Phi/\mathrm{dt}$ which drives a current I through the load resistor R_{LOAD}. The back mmf induced into the magnetic circuit is thus

$$U = -NI = -\left(\frac{N^2}{R_{LOAD}}\right)\frac{d\Phi}{dt} \qquad (5)$$

We can view the term in parentheses as a "magnetic inductance" L_M of value

$$L_M = \frac{N^2}{R_{LOAD}} \qquad (6)$$

since $U=-L_M\mathrm{d}\Phi/\mathrm{dt}$ has exactly the same form as $V=-L\mathrm{d}I/\mathrm{dt}$.

More details on dynamic analysis can be found in my paper "Analyzing Transformers in the Magnetic Domain".

3. A PM Generator.

Figure 1 shows a PM generator which has an idealized magnetic switch connecting a magnetic path from a magnet to a coil across which is connected a load resistor R_L. Clearly turning that switch sequentially on and off will cause flux through the coil to rise and fall and that will induce voltage into the coil hence power into the load. Figure 2 is the magnetic domain circuit showing the magnetic switch as having a value of shunt reluctance when open in the same way that an electric switch would have shunt capacitance.

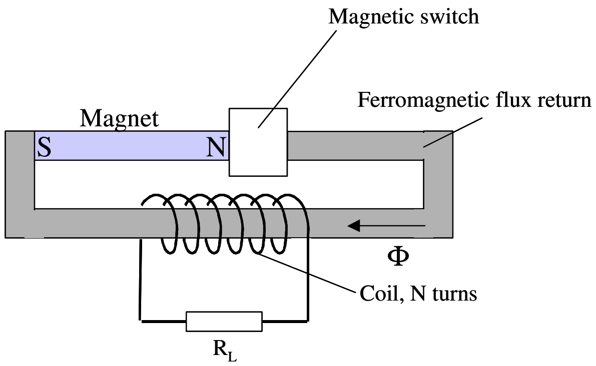

Figure 1. A PM Generator using a magnetic switch

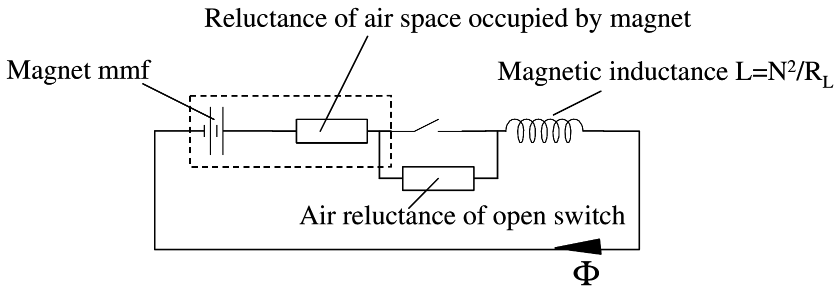

Figure 2. Magnetic domain circuit

Analysis of this magnetic circuit is quite trivial and will not be given here, suffice it to say that if the magnetic *L*/*R* time-constant is small compared to the time between switch operations the flux waveform is a square-wave with rise and fall times determined by that time constant. Note that only during those flux rise and falls is voltage induced into the coil to deliver power to the load in the form of a train of spikes. If the time constant is long the flux waveform becomes a triangular wave, hence the induced coil voltage becomes a square wave with power delivered almost continually.

One viable type of magnetic switch uses movement of ferromagnetic components relative to each other, so the switching action is not instantaneous but rather the gradual reduction of the shunt reluctance from a high value to a low value, hence figure 3 is a more realistic set-up. Here a ferromagnetic slug within a non-ferromagnetic rotor disc moves through an air gap thus changing its reluctance.

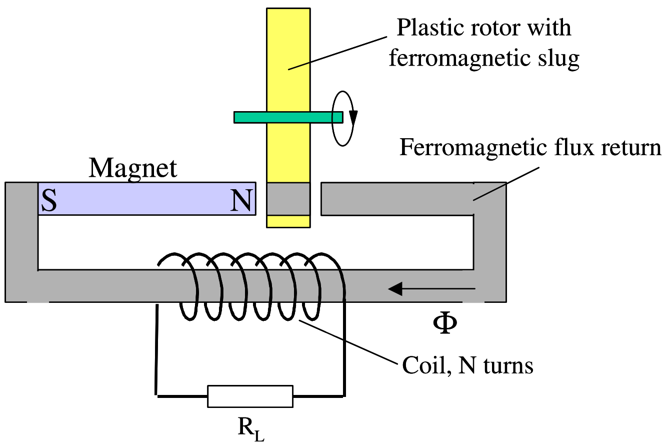

Figure 3. Variable reluctance generator

Figure 4 shows the magnetic domain circuit where the switch has been replaced by a variable reluctance.

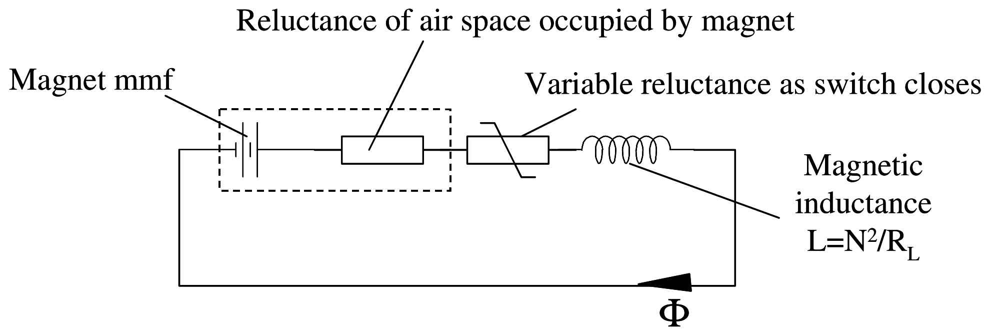

Figure 4. Magnetic domain circuit.

Note that the magnetic current (flux) flows through the mmf source inside the magnet. When that flux is changing not only is power being delivered to the load resistor but also the magnetic energy stored in the air-gap reluctance is changing. That stored energy W is given by

$$W = \Phi^2 R \tag{7}$$

The changing flux also draws energy from (or gives back energy to) the magnet's mmf source, power flow P being given by

$$P = U\frac{\mathrm{d}\Phi}{\mathrm{d}t} \tag{8}$$

Normally generators operate in a regime where the load resistor R_{LOAD} is much greater than the reactance of the coil, which is another way of saying the coil's L/R_{LOAD} time constant is small. Because of the relationships (3) between electrical inductance L and the internal reluctance R_M, and (6) between the magnetic inductance L_M and the electrical load resistor R_{LOAD}, the internal magnetic time constant L_M/R_M and the external electric time constant L/R_{LOAD} are the same. So the normal operating regime is where the internal magnetic circuit is dominated by the air reluctance, the energy extracted from the mmf flows between source and the reluctance, a negligible amount flows between the source and the magnetic inductor. It is then found that energy flowing into the load actually comes from the mechanical force needed to operate the magnetic switch, to move the ferromagnetic parts together or apart. Hence classical generators do not extract energy from the magnets. But within classical generators there exists that back and forth flow of energy between magnet and the air reluctance that so far has been ignored by the scientific community.

The situation is different if we move to a regime where the time constants are long which requires the load resistor to be very small. Then in the magnetic circuit the magnetic inductor L_M is very large and dominates the circuit. Now we have the situation where most of the energy extracted from the mmf source during a rising period of flux gets "stored" in the magnetic inductor, but that is actually energy dissipated in the load resistor. There is little energy change in the reluctance, in the field energy stored in the air gap. But what happens when the flux is falling after the switch is opened? Falling flux also produces an energy flow into the load resistor, while at the same time feeding energy back into the mmf source. This dilemma could be resolved when we consider the mechanical forces needed to operate the magnetic switch in this regime, and it is possible that they could completely explain the energy imbalance, there could be no overunity. However the eddy current heater detailed in international patent WO 03/0011002 "Magnetic Heater Apparatus and Method" assigned to MagTec LLC suggests otherwise. This describes a form of heater where an electrically conductive disc is rotated close to an array of permanent magnets. Eddy currents induced into the disc create heat that is transported away by contact with a fluid flow. Data is given on the performance of a heater where the fluid is air at a flow rate of 3200ft^3/min provided by a fan consuming 1.76KW, the air being raised in temperature by 80°F from contact with the heated disc driven by an electric motor consuming 20.9KW. This equates to a COP of 3.58. The preferred material for the disc is stated as Cu. This invention could provide important evidence that operating with low load resistance does extract energy from the mmf sources in the magnets.

From the simple equivalent circuit figure 4, summing the instantaneous mmfs around the closed path we obtain

$$U - \Phi R - L\frac{d\Phi}{dt} = 0 \qquad (9)$$

When the reluctance R dominates we find that $L \Rightarrow 0$ hence we obtain

$$\Phi \approx \frac{U}{R} \qquad (10)$$

from which we obtain

$$\frac{d\Phi}{dt} \approx \frac{-U}{R^2}\frac{dR}{dt} \qquad (11)$$

Thus $\frac{d\Phi}{dt}$, which is responsible for the voltage induced into the coil hence also the current through the load, comes predominantly from the changing reluctance, not from the magnetic inductance L. This is the situation that applies to classic generators, and that puts the peak coil current at an armature position that produces peak drag torque. Analyses of these generators show that, ignoring friction and windage losses, power delivered to the load resistor (which includes the coil resistance) always equates to shaft power needed to supply this torque.

Now consider the case where magnetic inductance L dominates equation (9) and we obtain

$$\frac{d\Phi}{dt} \approx \frac{U - \Phi R}{L} \qquad (12)$$

In a classical generator, which now has a very small load resistor across the coil, this shifts the peak coil current to an armature position where the torque is near zero. To test this hypothesis we need a full solution to the differential equation (9). Rearranging (9) into a standard form we obtain

$$\frac{d\Phi}{dt} + \frac{R}{L}\Phi = \frac{U}{L} \qquad (13)$$

for which the solution for Φ may be obtained from

$$\Phi \exp\left(\int \frac{R}{L} dt\right) = \int \left[\frac{U}{L} \exp\left(\int \frac{R}{L} dt\right)\right] dt + C \qquad (14)$$

For the first integral, if R varies with time in a sinusoidal manner, a direct solution exists. Unfortunately for the second integral it appears there is no direct solution available, the Wolfram on-line integrator cannot find one. Thus it requires an iterative approach, which has been done on a spreadsheet using Simpson's Rule for the second integral. Magnetic reluctance was modeled as $R_M = R_0 + R_{PEAK}\sin(\omega t)$ using practical values. The solution was obtained over 10 cycles of a 100Hz waveform with the results shown below. Chart 1 shows the variation of the total reluctance from time zero. Chart 2 shows the flux waveform for a 20Ω load resistor where it is seen that the flux develops its cyclic nature almost immediately. This is because at that load resistance the magnetic time constant is 1.57×10^{-4}, a small part of a cycle. The phase correlation between the reluctance R_M and the flux Φ is seen more easily in the expanded charts 3 and 4 which show the last two cycles. Note that maximum flux occurs at minimum reluctance.

Chart 5 shows the flux for a load resistance of 0.2Ω where the magnetic time constant is now 100 times greater. The flux is seen to build up from time zero before settling down into the cyclic regime. Chart 6 shows the last two cycles to compare with chart 4 where it is seen that the flux waveform has shifted by almost 90 degrees. This confirms the existence of this phase delay in the magnetic domain. Note that maximum rate of change of flux now occurs at positions where the reluctance is maximum or minimum. These occur when the rotor ferromagnetic slug is either in full alignment with the gap or furthest away. At these positions the torque is zero, the load current has no influence on the torque.

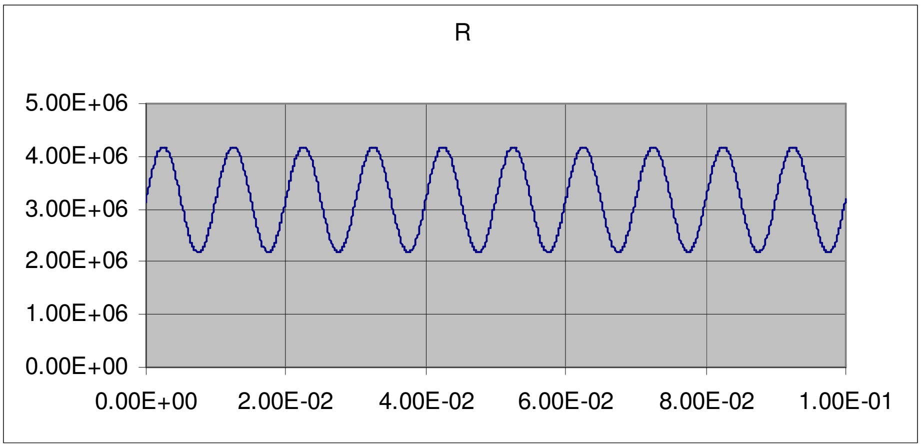

Chart 1. Variation of Reluctance with time

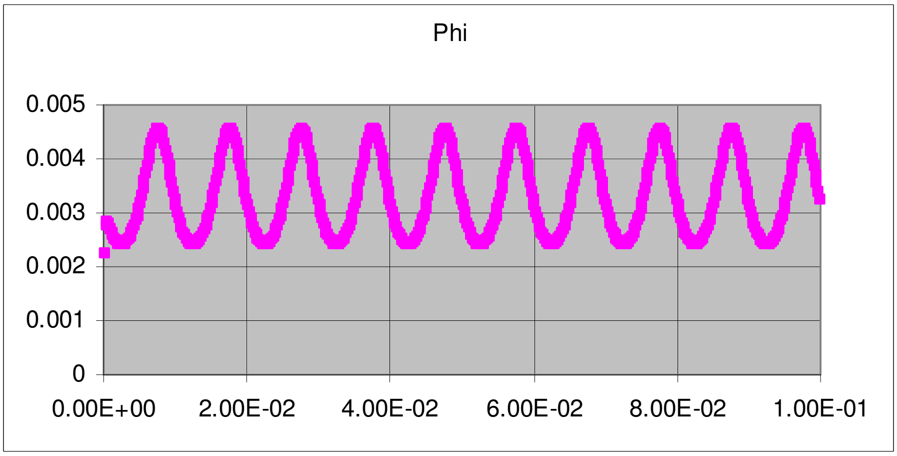

Chart 2. Flux waveform for short magnetic time-constant

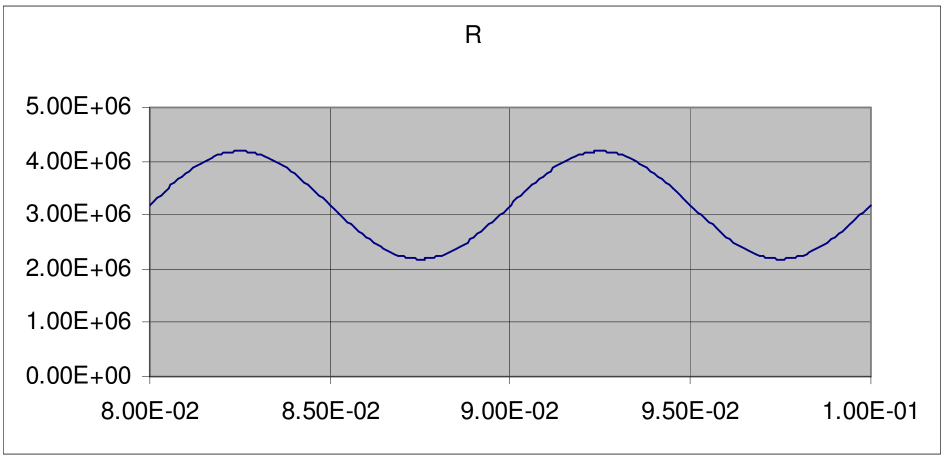

Chart 3. Last 2 cycles of Reluctance waveform

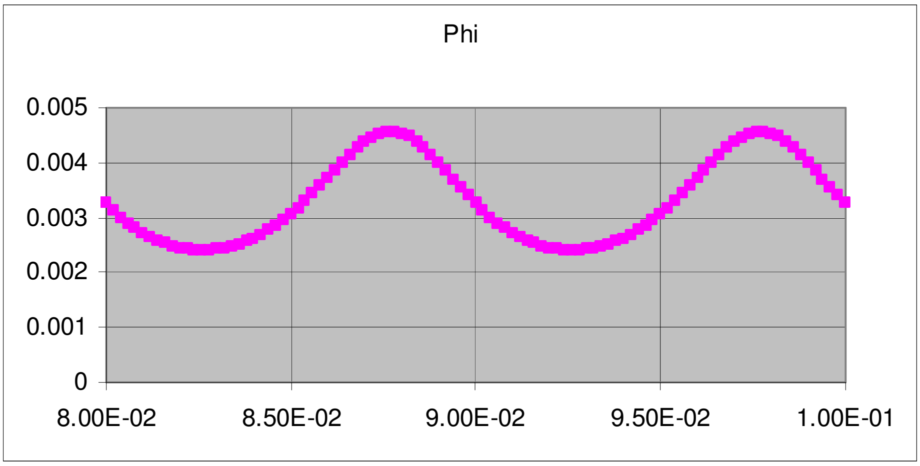

Chart 4. Last 2 cycles of flux waveform for short magnetic time-constant

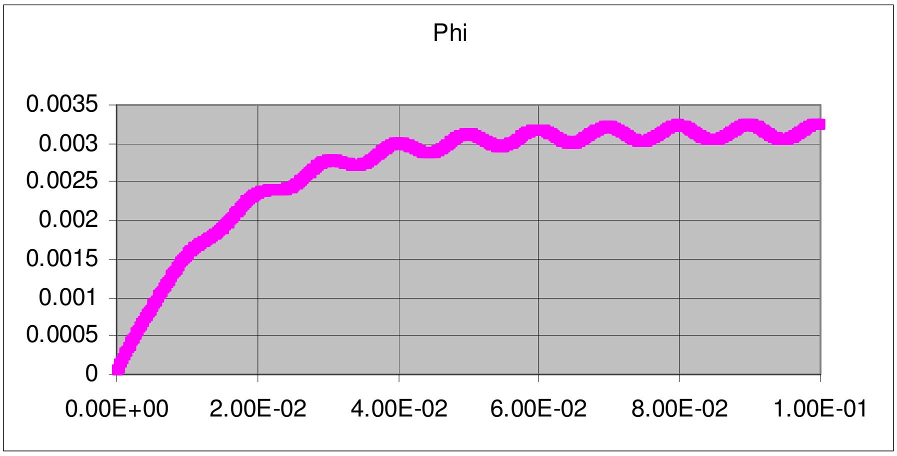

Chart 5. Flux waveform for long magnetic time-constant

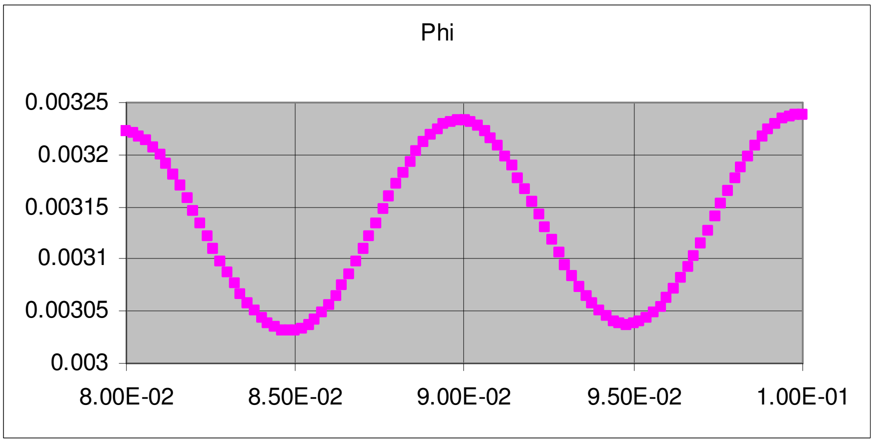

Chart 6. Last 2 cycles of flux waveform for long magnetic time-constant

4. Conclusion

Dynamic analysis of the magnetic domain circuit of a generator shows that when heavily loaded the flux waveform is phase shifted by 90º which presents the peak load current at an armature position where it cannot produce torque. This offers the possibility of creating an OU generator, the down side being that the load resistor has to be lower than the normal loss resistance of the coil. Thus the possibility of this is normally hidden from view, the classic generator running at such low resistance loads (a) dissipates most of its energy in the coil hence is very inefficient and (b) because of the finite coil resistance doesn't reach the OU region anyway. One example of a generator that does reach this OU region is the eddy-current heater detailed in international patent WO 03/0011002 where the coil is effectively just the eddy current loops. However the analysis has identified what is needed to engineer a system that can provide this energy in electrical form to an external load. It is clear that when room temperature superconductors become available such a system is easily produced, but meanwhile we have to contend with coils with minimum turns and maximum copper. And since we need very low load resistance applied to such a coil, it would seem sensible to eliminate slip-rings or commutators by having the coil fixed while the magnet(s) move. This arrangement inevitably yields AC, so the obvious thing to do is employ a step-up transformer between the coil and the final load, thus applying a very low value load to the coil.